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Ning et al.

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(54) **HIGH PERFORMANCE LENSES**

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G02B 13/00 (2006.01)
G02B 9/64 (2006.01)
G02B 9/62 (2006.01)

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CPC ***G02B 13/005*** (2013.01); ***G02B 9/62*** (2013.01); ***G02B 9/64*** (2013.01)

(58) **Field of Classification Search**
CPC G02B 13/0045; G02B 13/04; G02B 9/34
USPC 359/715, 753, 771, 781, 783
See application file for complete search history.

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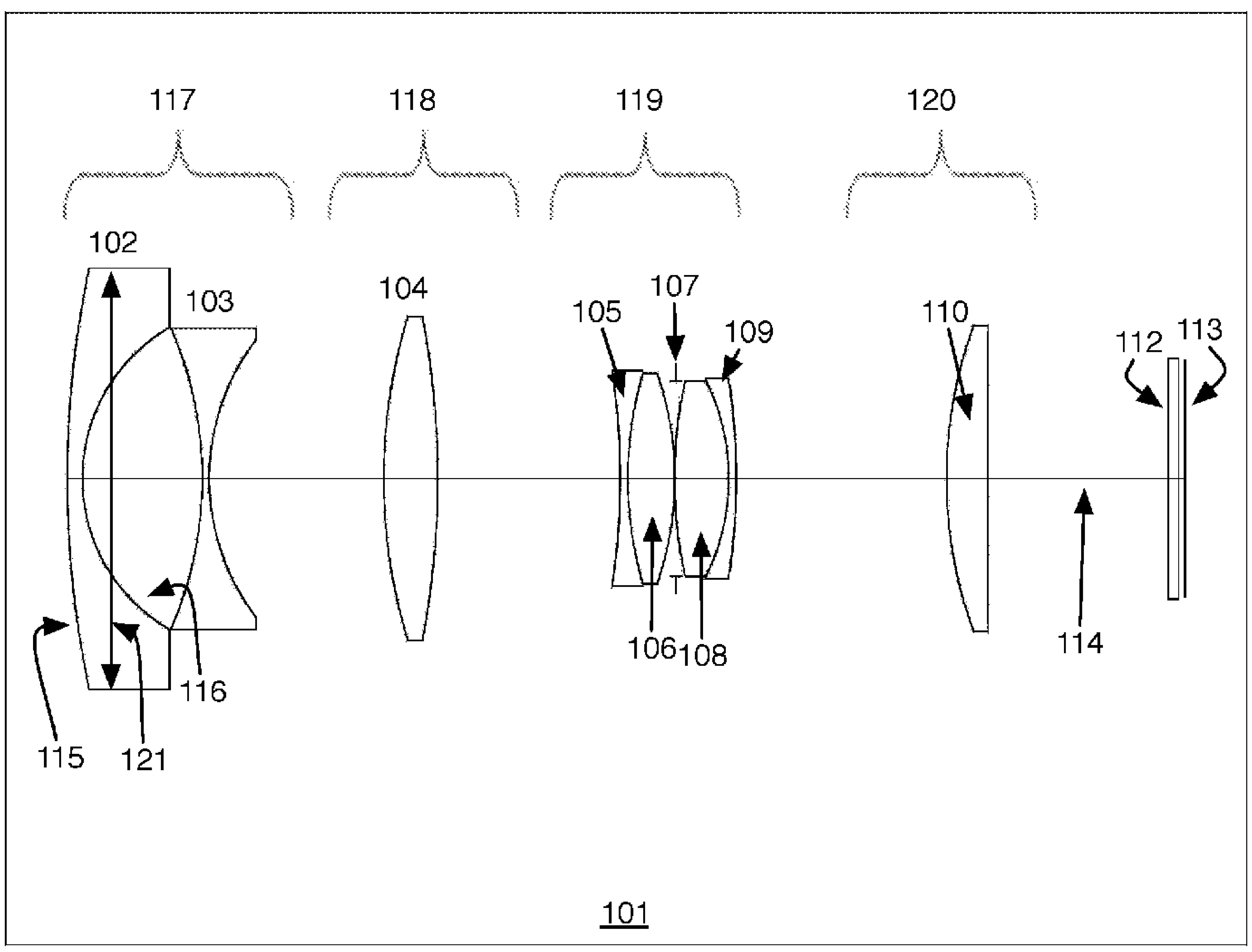
(57) **ABSTRACT**

High performance lens system designs are described. The lens system has four lens groups, is made entirely of spherical lens elements, and, includes selected lens elements made of materials with high refractive index and Abbe numbers and coefficient of thermal expansion that provide stable high performance across wide and rapid temperature changes. Group descriptions and parametric equations enable creation of designs having fields of view ranging from 50 to 150 degrees.

8 Claims, 12 Drawing Sheets



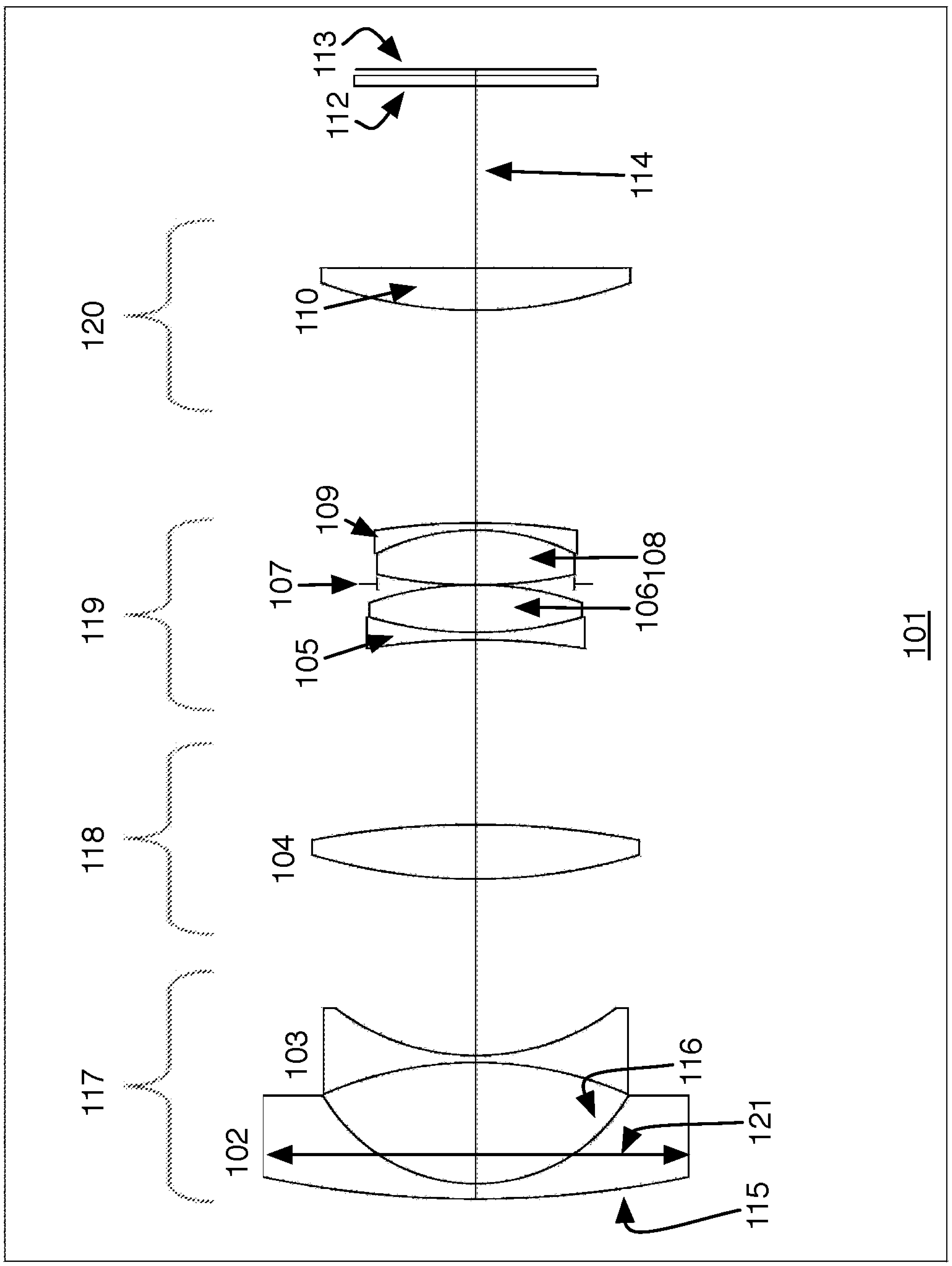

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Figure 1

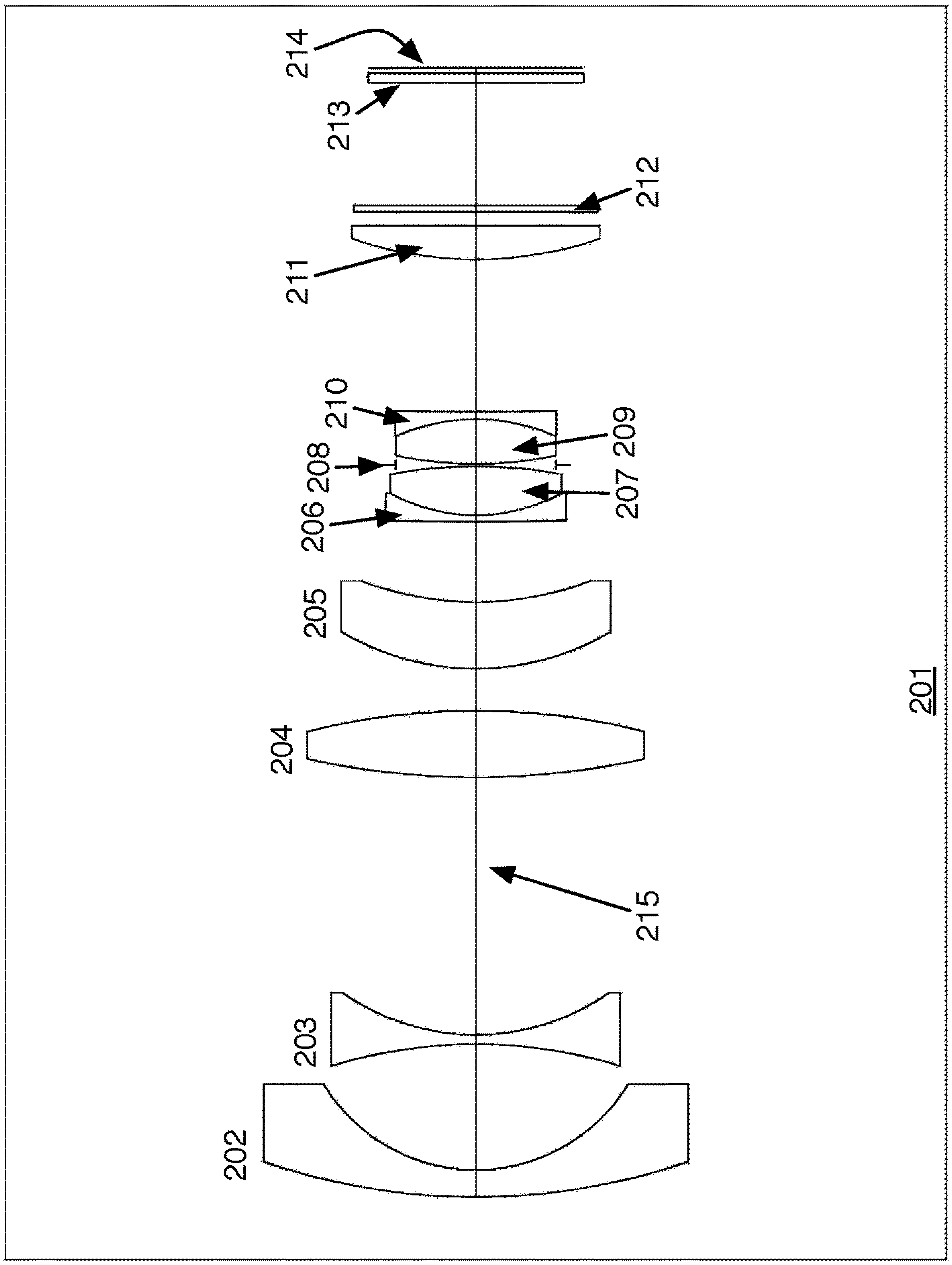


Figure 2

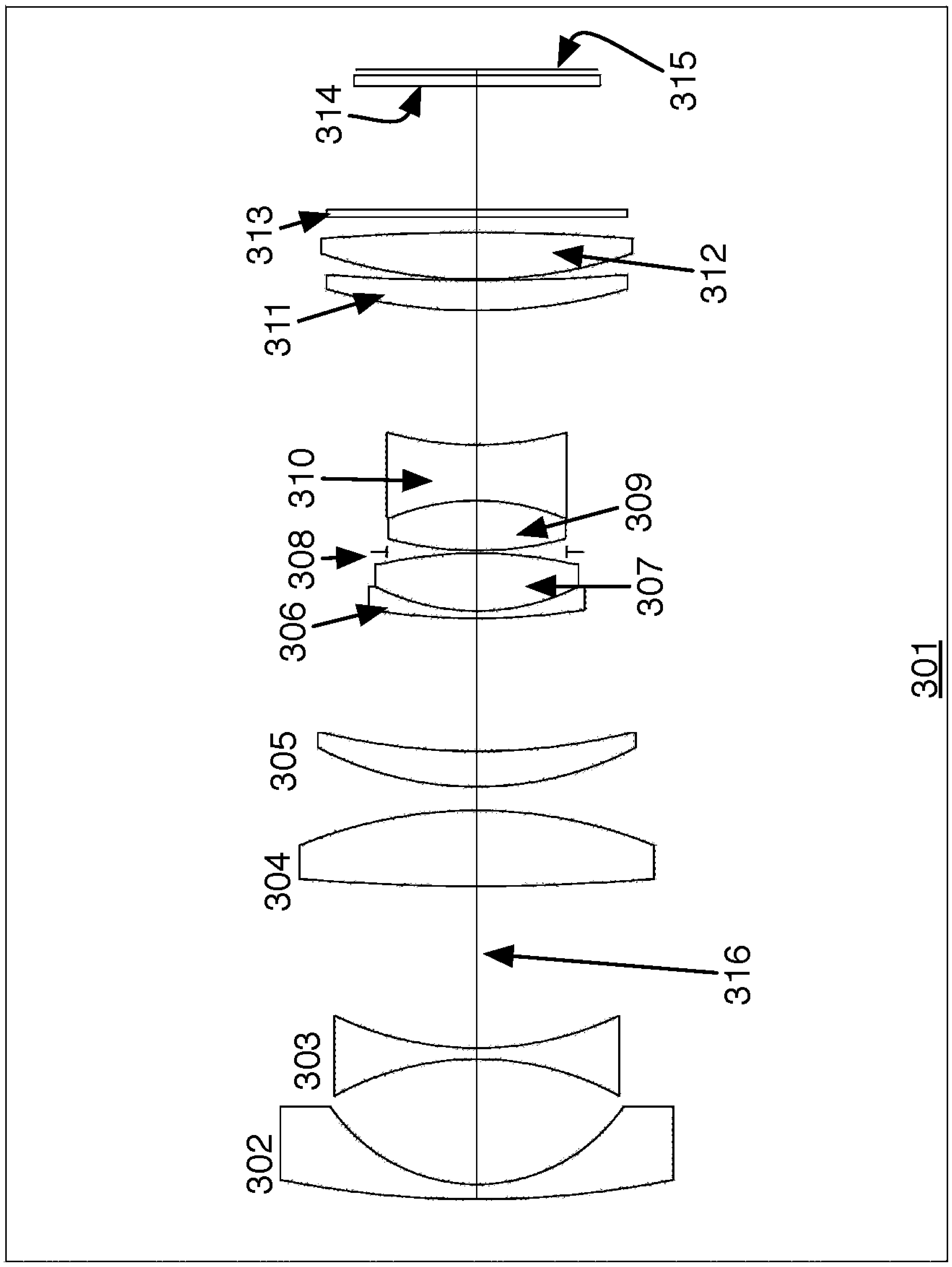


Figure 3

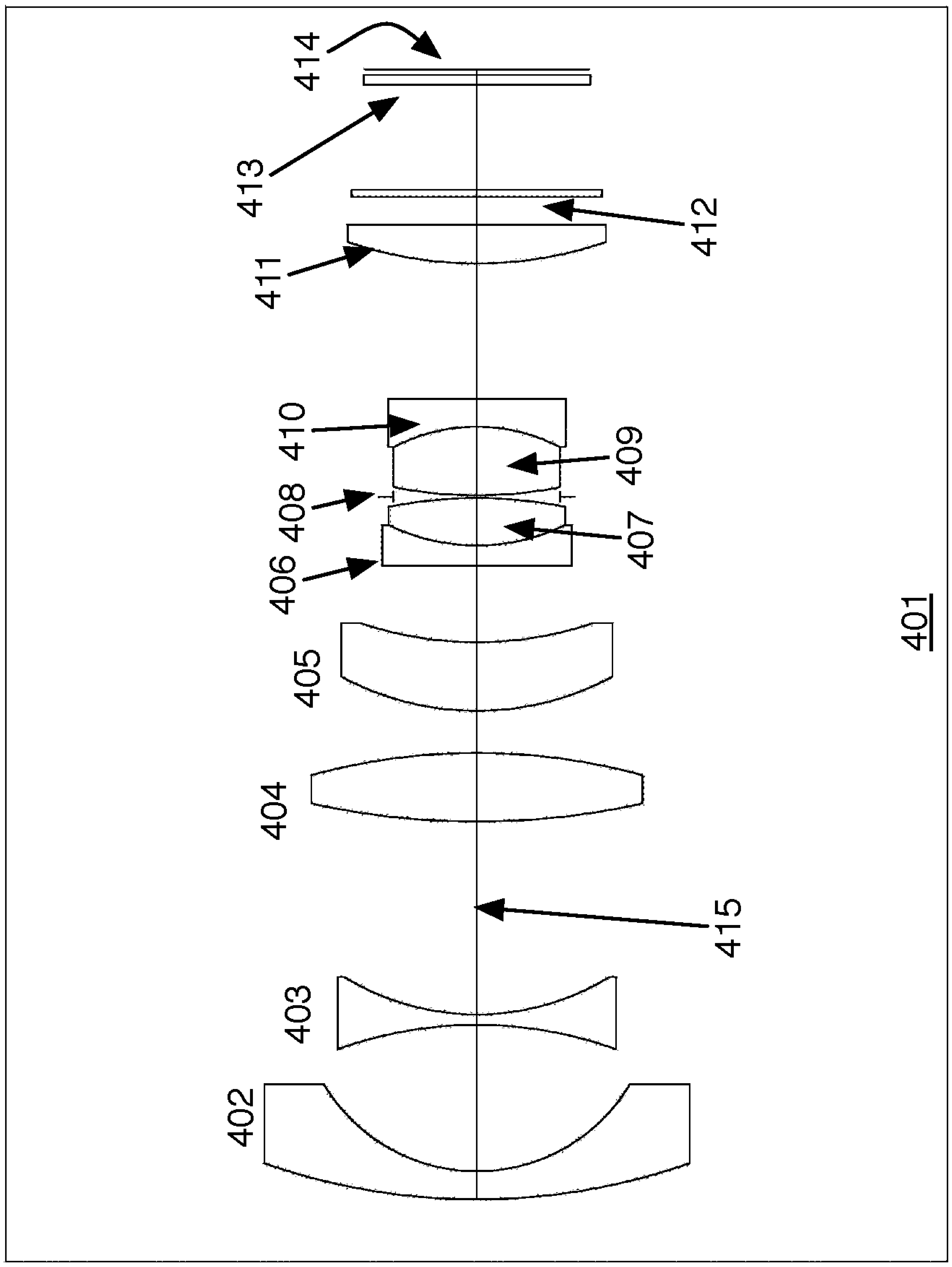


Figure 4

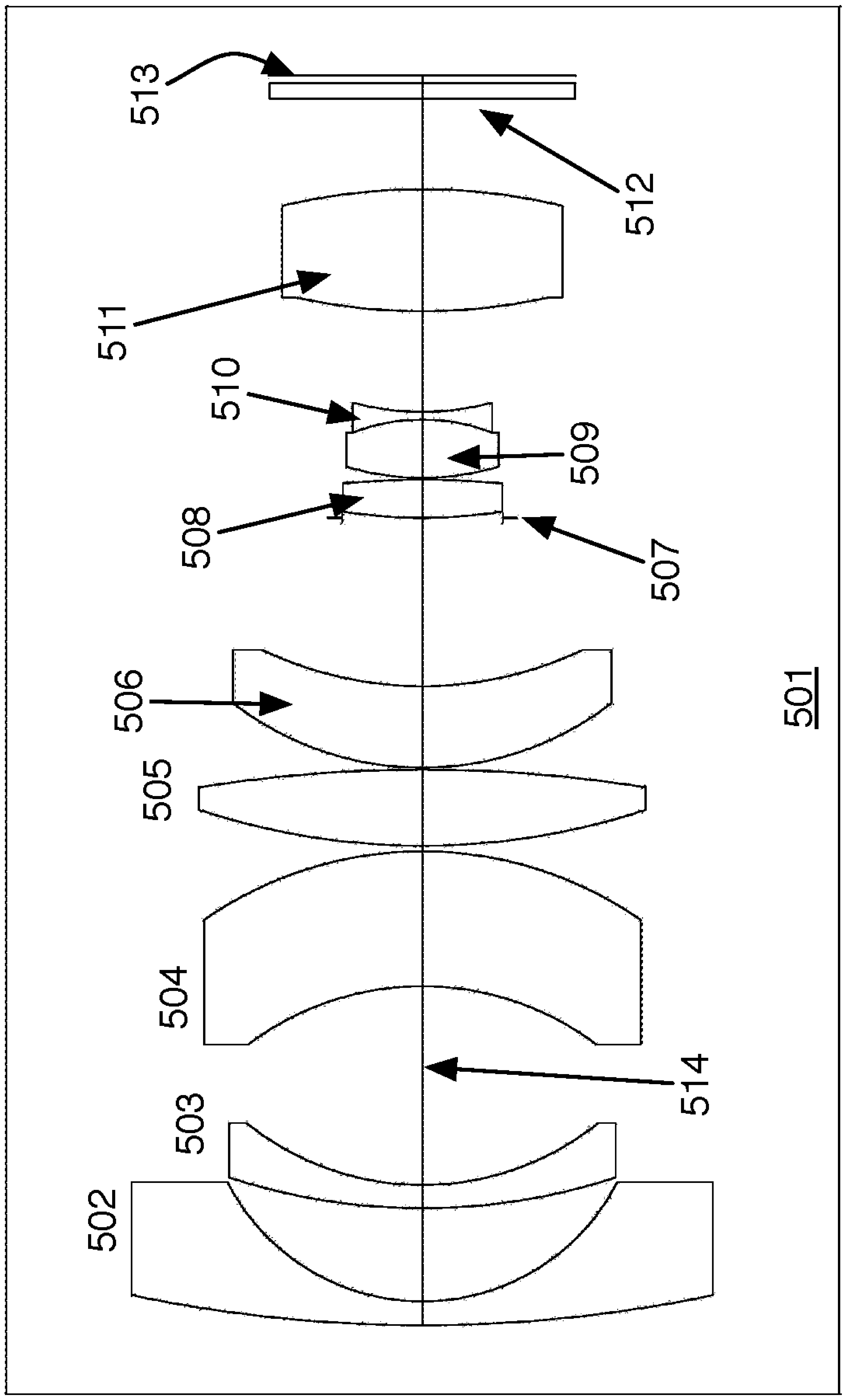


Figure 5

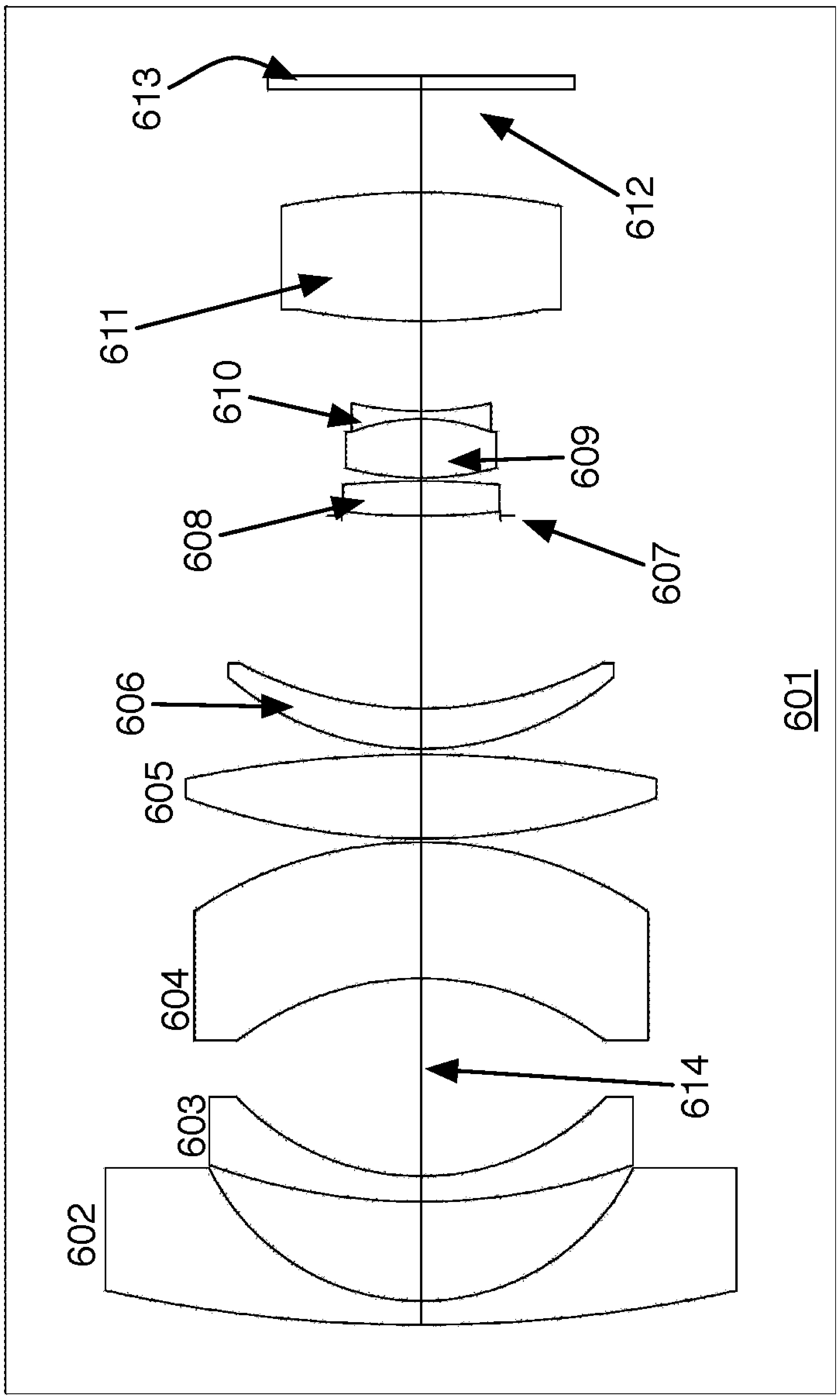


Figure 6

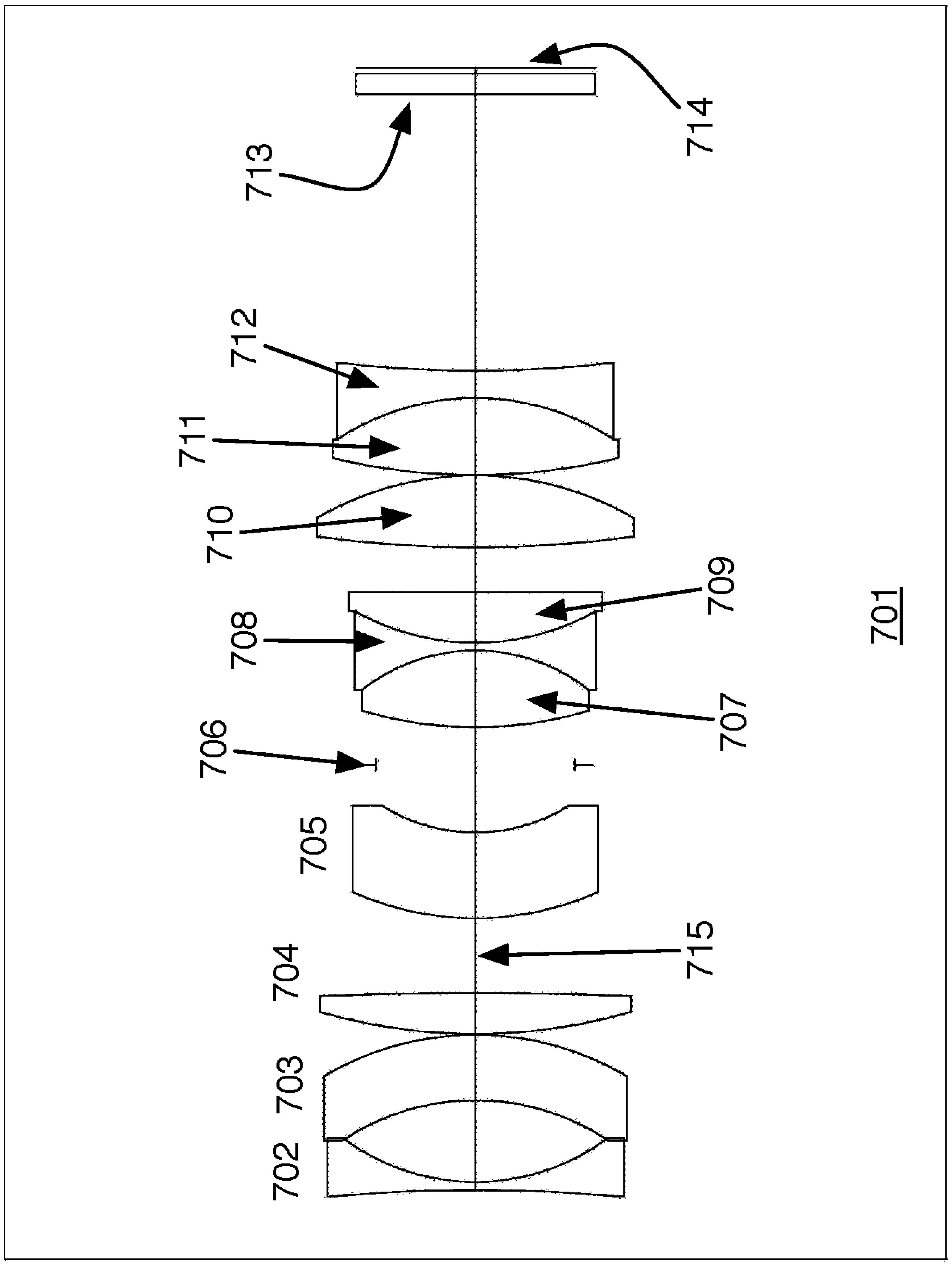


Figure 7

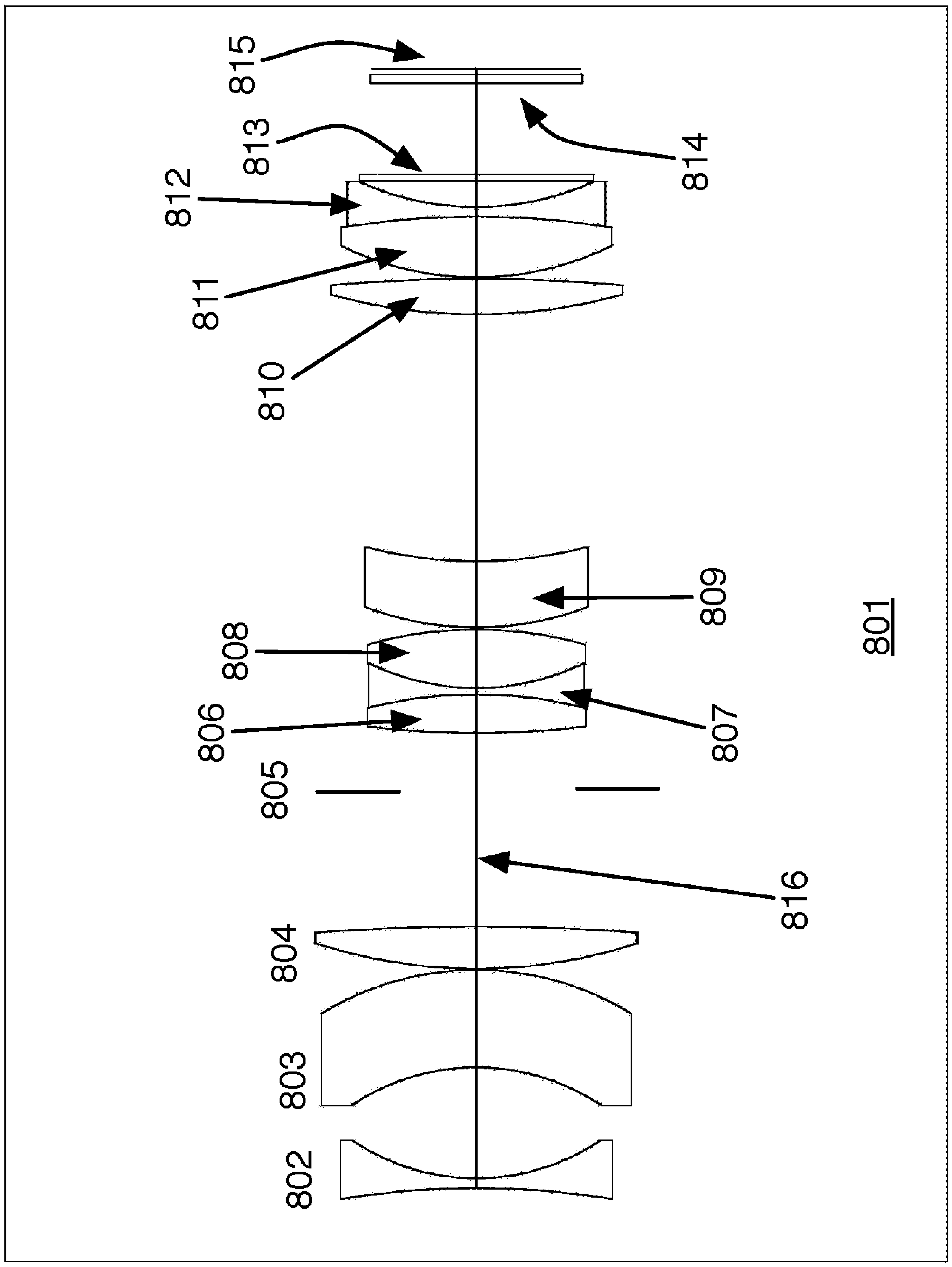


Figure 8

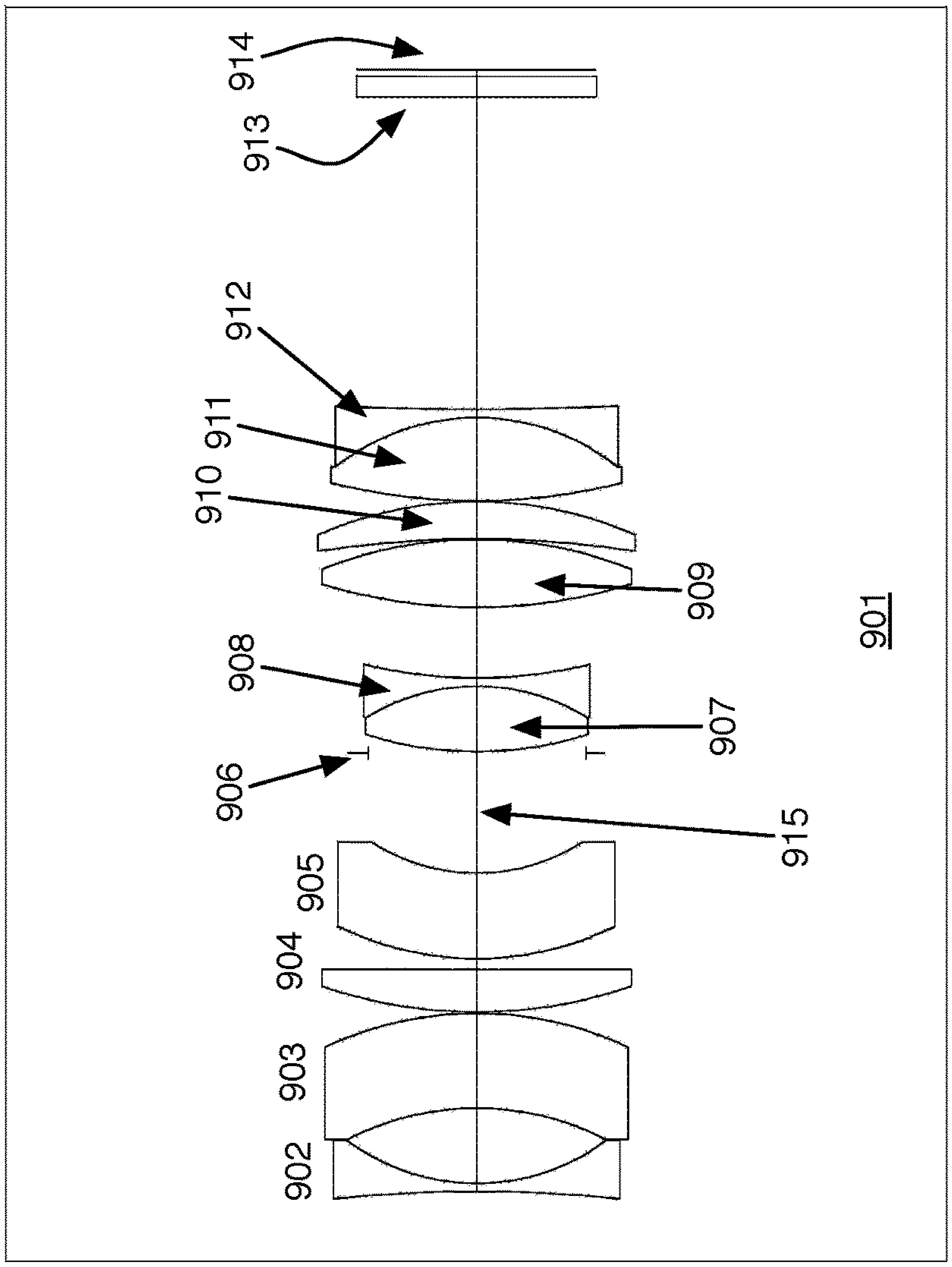
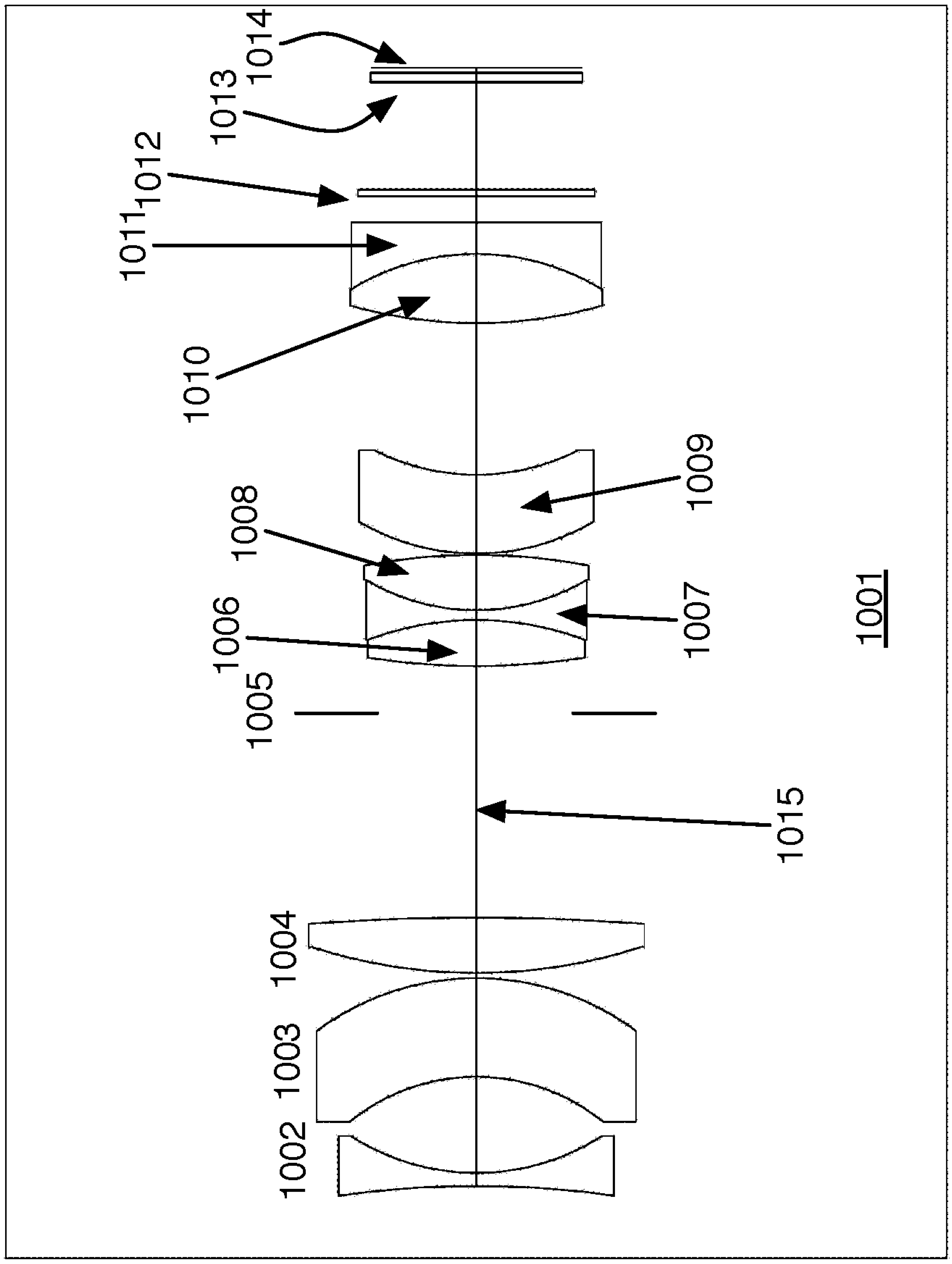


Figure 9


1001
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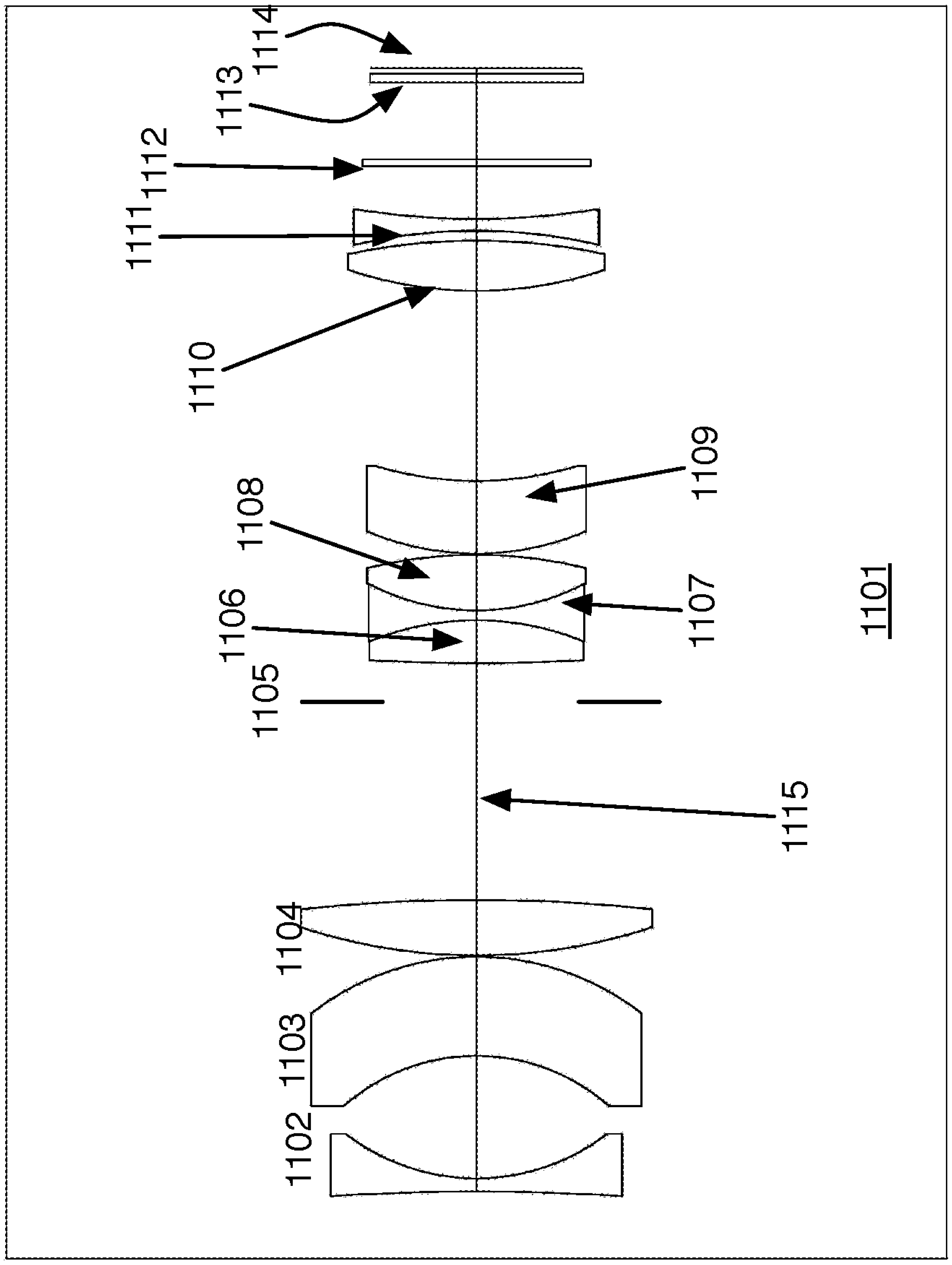
1005
1006
1007
1008
1009
1010
1011
1012
1013
1014
1015

Figure 10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1115
1104
1103
1102
1101

Figure 11

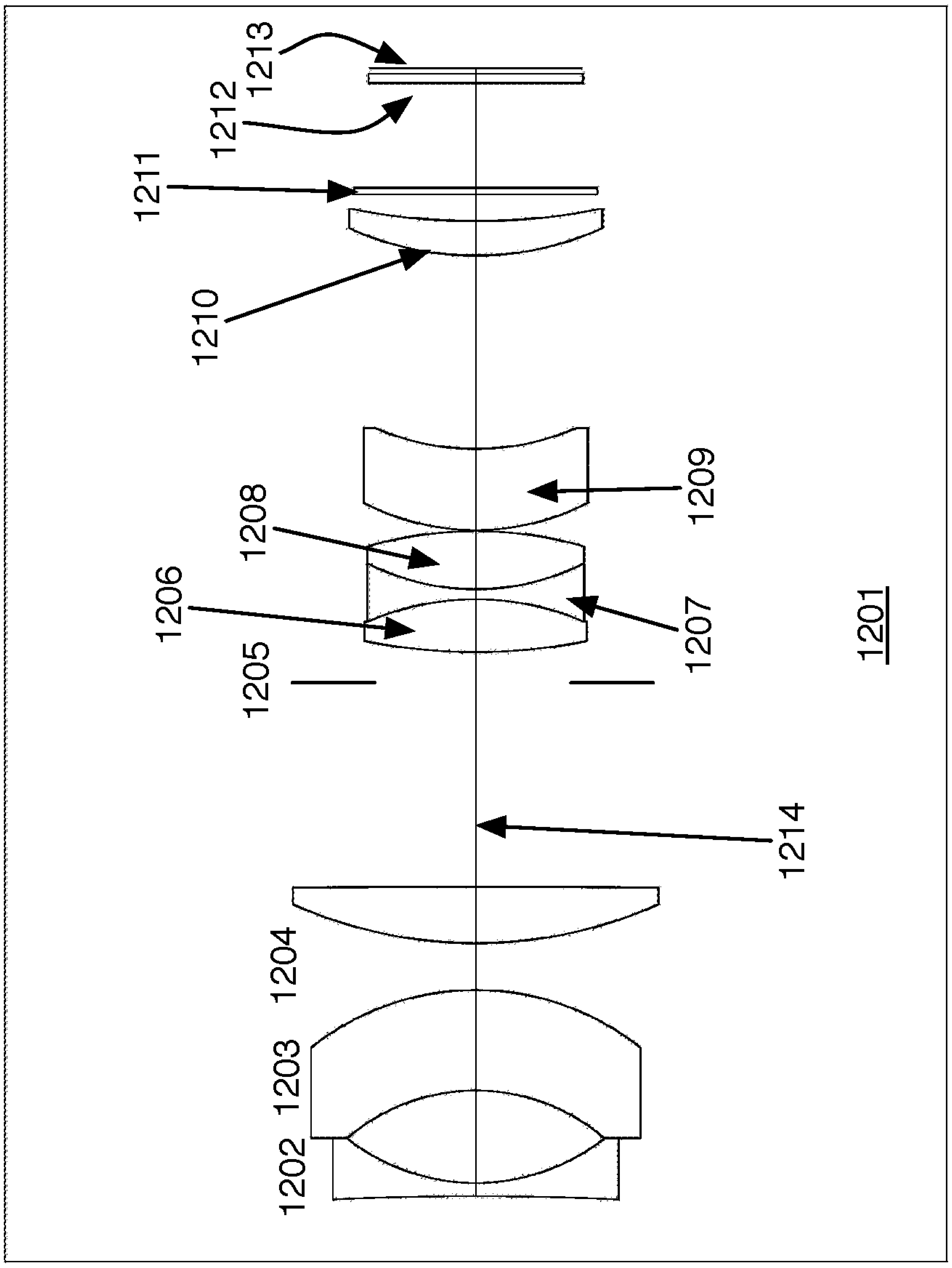
1213
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Figure 12

HIGH PERFORMANCE LENSES

CROSS-REFERENCE TO RELATED APPLICATIONS

This application claims priority to U.S. Provisional Application 62/551,078, titled Wide-angle high performance lenses, filed Aug. 28, 2017, and, U.S. Provisional Application 62/400,952, titled high performance lenses, filed Sep. 28, 2016, both including a common inventor.

STATEMENT REGARDING FEDERALLY SPONSORED RESEARCH OR DEVELOPMENT

Not Applicable.

BACKGROUND OF THE INVENTION

Technical Field

The invention relates to wide-angle lenses, having high quality images across the entire field of view in a compact form factor.

Related Background Art

Digital imaging cameras use solid-state image sensors such as CCD or CMOS imagers to convert optical images into electronic signals. As the resolution of the imagers increases, there is a continuous need for optical lenses with increased performance. An important characteristic of the lens is the ability to produce high-resolution images across a wide field of view. Another important characteristic is to produce such high-resolution images using a lens that is of a compact size. The lenses are increasing being incorporated into a variety of electronic devices including mobile phones, cameras, sports cameras, computers and computer peripherals. Incorporation of the lenses into new devices also places new environmental performance requirements upon the lens. The lens must be compact and light, to be used in portable devices, and must maintain high performance characteristics.

The quality and pixel density of very small imaging sensors is continuously improving. The sensors are used in machine vision, medical, cell phone and automotive applications. In many cases low distortion is critical to proper functioning in the intended application. These lenses are being used more and more in consumer application where literally millions of such lens systems must be easily produced at consistent high quality and at low cost. Custom lens features required to produce low distortion must be designed such that they are also easy to manufacture. The lenses also are now subject to more extremes in environment. A lens that exhibits low distortion and performs consistently across a wide and rapidly changing temperature range is required.

Frequently aspheric elements have been used for improved lens performance. However, if the aspheric lenses are made from plastic the higher temperature variation of plastic precludes their use in a varying environment. Aspheric lens can be made of glass as well, but that adds greatly to the difficulty to manufacture and cost of a lens and may preclude their use in high volume cost sensitive applications.

Distortion cannot be fully corrected through mathematical manipulation of the digital images, in order for such corrections to be effective requires that the lens manufacturer produces a well behaved lens.

There is a need for new lens designs that exhibit low color aberration and optical distortion that follows the f-tan relationship, the lens is a compact lens and maintains optical performance over a wide range of, and rapidly changing, temperatures.

There is a need for new lens designs that exhibit low color aberration and low optical distortion that are constructed of glass and avoid the use of aspheric lens elements.

There is a need for a lens design that can cover the range from medium to wide angle field of view.

There is also need to provide medium and wide-angle lens designs that can be manufactured inexpensively, consistently and can be automatically assembled.

BRIEF SUMMARY OF THE INVENTION

The objective of this invention is to provide high performance imaging lenses with low F-numbers having narrow and wide angle of view. High performance imaging lenses are characterized by low f-number (<2), high resolution, wide spectral range, low chief ray angle, and stability with respect to a change in environmental conditions such as temperature. They also a need to achieve various field of views from narrow (about 50 degrees) to wide (about 150 degrees). To achieve the stated objective, the present invention includes optical materials in selected lens elements with low Abbe numbers exceed 63, or/and a negative dn/dT value, where n is the index of refraction of the material at d-line, and T is a temperature of an environment containing the optical lens. There are four groups from the object side to the image side (left to right):

1) Group 1 has negative power and consists of one or two elements. All elements in group 1 have negative power.
2) Group 2 has positive power comprising 1 to 3 elements.
3) Group 3 comprises at least a cemented doublet or a cemented triplet, where the positive element of the doublet or at least one of the positive elements of the triplet is made of a low dispersion material having an Abbe number greater than 63. In preferred embodiments, at least one of the positive elements of the doublet or triplet is made of an optical material having a negative dn/dT over the operating temperature range, typically −40 to +85° C., where n is the index of refraction of the material at d-line, and T is the temperature of the environment. In preferred embodiments, group 3 includes two cemented doublets with the aperture stop between them. In one embodiment, an optional meniscus lens element is positioned adjacent to the doublet or the triplet. An aperture stop is adjacent to or embedded in this group. In preferred embodiment the aperture stop is on the object side of the cemented triplet or embedded within a pair of doublets.
4) Group 4 has positive power comprising 1 to 3 elements

Optical filters and cover glasses for the image sensor are optionally added after the fourth lens group.

The lenses satisfy the following parametric equations:

$$-2 =< F1/F =< -0.8 \quad (1)$$

$$1.5 =< F2/F =< 3.5 \quad (2)$$

$$2. =< |F3/F| \quad (3)$$

$$1. =< F4/F =< 3.5 \quad (4)$$

$$-3 =< F4/F1 =< -0.6 \quad (5)$$

$$0.3 =< F4/F2 =< 2.5 \quad (6)$$

Where F is the focal length of the entire lens assembly and Fi is the focal length of lens group i.

In preferred embodiments the following equation is satisfied by Group 1:

$$-1.6 =< F1/F =< -0.8 \quad (7)$$

The examples fall into two general categories: wide angle lenses with a field of view greater than 100 degrees and narrow angle lenses with a field of view of about 50 degrees. Both categories satisfy the descriptions and parametric equations discussed above.

The specific examples are not intended to limit the inventive concept to the example application. Other aspects and advantages of the invention will be apparent from the accompanying drawings and detailed description.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** is a diagram of a first embodiment of the high performance lens.

FIG. **2** is a diagram of a second embodiment of the high performance lens.

FIG. **3** is a diagram of a third embodiment of the high performance lens.

FIG. **4** is a diagram of a fourth embodiment of the high performance lens.

FIG. **5** is a diagram of a fifth embodiment of the high performance lens.

FIG. **6** is a diagram of a sixth embodiment of the high performance lens.

FIG. **7** is a diagram of a seventh embodiment of the high performance lens.

FIG. **8** is a diagram of an eighth embodiment of the high performance lens.

FIG. **9** is a diagram of a ninth embodiment of the high performance lens.

FIG. **10** is a diagram of a tenth embodiment of the high performance lens.

FIG. **11** is a diagram of an eleventh embodiment of the high performance lens.

FIG. **12** is a diagram of a twelfth embodiment of the high performance lens.

DETAILED DESCRIPTION OF THE INVENTION

The description of the lens elements as flat, convex or concave refers to the curvature at this point on the lens surface that intersects the optical axis. The term lens refers to the lens system that is comprised of a plurality of lens elements. Each lens element by itself is also known in the literature as a lens. Here, lens system may refer to the multi-component system or an individual lens element within the lens system. In all cases the meaning will be clear from context and form reference numbers.

Referring to FIG. **1** an invented lens system **101** is shown. The lens system **101** is shown in a cross-sectional profile, as are all of the subsequent lens system designs. The lens system **101** is centered on the optical axis **114**. The lens system is oriented such that the object side is to the left and the image side is to the right. The lens or lens system **101** is comprised of a plurality of lens elements **102-106** and **108-110** and includes an aperture stop **107**. The image plane **113** is at the right edge of the lens system. It is the location of an optical imaging device such as a CCD or CMOS imagers to convert optical images into electronic signals as are known in the art. The particular example of FIG. **1** includes, from object to image, four lens groups **117-120**. There are four groups from the object side to the image side (left to right):

1) Group 1 has negative power comprising two elements **102**, **103**.

2) Group 2 has positive power comprising 1 to 3 elements, in this case a single lens element **104**.

3) Group 3 comprises at least cemented doublet or cemented triplet, where the positive element of the doublet is made of lowa low material having Abbe number greater or equal to 63. In preferred embodiments, group 3 includes two cemented doublets with the aperture stop between them. In this specific example, two cemented doublets are included **105**, **106** and **108**, **109** low. The first positive element **106** has an index of refraction of 1.59 and an Abbe number of 68.6 a d the second positive element has an index of refraction of 1.46 and an Abbe number of 90.2. In a preferred embodiment, at least one of the positive elements **106**, **108** of the doublet or triplet is made of an optical material having a negative do/dT over the operating temperature range, where n is the index of refraction of the material at d-line, and T is the temperature of the environment. Such materials may include FCD505 and FCD10A glasses made by Hoya Optical glasses. An aperture stop **107** is embedded in this group. In preferred embodiment the aperture stop is on the object side of the triplet or embedded within a pair of doublets. In this case the aperture stop is embedded in the pair of cemented doublets.

4) Group 4 has positive power comprising 1 to 3 elements, in this case a single lens element **110** comprises group 4.

Further details of this first example include, the first lens group **117** is comprised of two lens elements **102**, **103**. The first lens element **102** has a convex object surface **115** and a concave image surface **116**. The second lens element **103** is, in this example, a biconcave lens element. The second lens group **118** is comprised of a single lens element **104**. The third lens group **119** is comprised of two cemented doublets **105**, **106** and **108**, **109**. There is an aperture stop **107** located between the cemented doublets. The fourth lens group **120** is comprised of a single lens element **110**. All of the lens elements are situated symmetrically along the optical axis **114** of the lens system **101**. An optional cover glass **112** for the imaging device located at the image plane **113** is also included. The lens system of FIG. **1** satisfies the general description discussed above of a lens system with four lens groups and satisfies all of the parametric equations 1-6. The detailed parameters for each of the lens elements of this first example are shown in Table 1. Similarly details for each of the subsequent included in FIGS. **2-12** are presented in the same format in subsequent tables 2-12 respectively. Each of the lens examples include a specification for each lens element. The specification includes material properties such as index of refraction and Abbe number as well as surface curvature, thickness of the lens elements and spacing between lens elements The radius of curvature for each lens element is measured at the intersection of each surface with the optical axis **114**. Surfaces are numbered consecutively from object to image. Thus surface 1 is the first surface **115** of the first lens element **102**. Surface 2 is the second or image side surface **116** of the same lens element. Surface 3 is the first, object side, surface (not labeled) of the second lens element **103** and so forth through all elements of the lens system **101**. Thickness is defined as the distance from the surface to the next labeled surface measured along the optical axis **114**. For example, in the Table 1 the thickness of the first lens element **102**, the distance between the first surface **115** and the second surface **116** of that lens element, and is 1.00 mm. The distance from the image side surface **116** to object side surface of the second lens element is 8.06 mm. Nd in Table 1 is the index of refraction, and, Abbe # is the Abbe Number for the lens element corresponding to the designated surface at 578 nm (d-line). For example, the index of refraction of the first lens element **102** is 1.44 and the Abbe Number of the first element **102** is 95.10. The values for Radius and Thickness values are all given in mm. The values may be scaled by the effective focal length and the design may therefore be scaled for a lens of any focal length. The table of parameters for all subsequent examples uses the same format as shown in table 1.

Specific examples satisfying the description of the invented high performance lenses follow. Each of the examples represent a wide angle lens with a field of view of between 50 and 140 degrees, are comprised of four lens groups as described above, satisfy equation 1-6, include no aspherical elements or plastic lens elements, and, include at least one lens element with a high Abbe number.

Examples 1-6 show lens systems that satisfy the design parameters including the description of the four lens groups and the parametric equations 1-6 and have a field of view between 97 and 145 degrees.

Examples 7-12 show lens systems that satisfy the design parameters including the description of the four lens groups and the parametric equations 1-6 and have a field of view of 51 degrees.

The particular designs are provided as examples. Designs satisfying the description including the parametric equations can be made with any lens angle between 50 and 150 degrees.

Example 1

FIG. **1** shows the layout of Example 1. The design is, as already discussed above, comprised of, from object to image, of four lens groups. The first lens group **117** has two negative lens elements **102**, **103**, the second lens group **118** is comprised of a single positive lens element **104**. The third lens group **119** is comprised of a pair of cemented doublets. The first includes lens elements **105**, **106** and the second includes the two lens elements **108**, **109**. An aperture stop **107** is situated between the two cemented doublets of the third lens group. At least one positive element of the cemented doublets of the third lens group is made of materials having a high abbe number and has a negative coefficient for the change of refractive index (D-line) versus temperature. In this case positive lens element **108** is made from material having a high Abbe number (90.2) and a negative do/dT. The fourth lens group **120** includes a single positive lens element **110**. This design has a field of view of 94°, with a relative aperture of F/1.8. Table 1 shows the optical specification for this first example. The surfaces are numbered as already described. The radiuses of curvature are measured at the optical axis **114**. The column Lens Element refers to the numbered lens elements of FIG. **1**. The conic constant for all surfaces in this example and all others is 0. The surfaces in all of the examples are spherical surfaces. The EFL of this example 1 is 10.2 mm. The conditional expressions (1) through (6) are satisfied.

TABLE 1

The optical prescription of Example 1.

Surface	Radius	Thickness	Nd	Abbe#	Lens Element
1	69.14	1.01	1.44	95.10	102
2	11.69	8.06			
3	−25.16	0.46	1.44	95.10	103
4	15.36	11.73			
5	37.44	3.63	1.95	32.32	104
6	−57.14	12.27			
7	−45.75	0.50	1.67	32.17	105
8	25.01	3.17	1.59	68.62	106
9	−21.20	0.06			
STO	Infinity	−0.08			
11	31.12	3.65	1.46	90.19	108
12	−14.68	0.48	1.85	23.78	109
13	−45.39	14.14			
14	29.73	2.80	2.00	29.13	110
15	2031.60	12.11			
16	Infinity	0.70	1.52	64.21	
17	Infinity	0.40			
IMA	Infinity				

Example 2

FIG. **2** shows the layout of Example 2. This design has a field of view of 97° with a relative aperture of F/1.8.

There are four groups in lens system **201** of Example 2 comprising, from the object side to the image side (left to right):

1) Group 1 has negative power and consists of two negative power elements **202**, **203**.
2) Group 2 has positive power comprising 1 to 3 elements, in this example Group 2 is comprised of two lens elements **204**, **205**.
3) In this particular example Group 3 is comprised of a pair of cemented doublets **206**, **207** and **209**, **210** with an aperture stop **208** embedded between the doublets. There is no optional meniscus element in this example. The positive elements **207**, **209** of the cemented doublets are made from a material having low dispersion properties in that the index of refraction and Abbe number of the first positive element **207** are 1.59 and 68.6 respectively and the index of refraction and Abbe number of the positive element **209** of the second doublet are also 1.59 and 68.6 respectively. Both positive lens elements **207**, **209** have a negative value for do/dT.
4) Group 4 has positive power comprising 1 to 3 elements. In this case group 4 is comprised of a single element **211**.

The lens elements are all arranged symmetrically about the optical axis **215**. The design further includes an optional optical filter **212** and a cover **213** covering an image sensor located at the focal plane **214**. Optical filters and cover glasses for the image sensor are optionally added after the fourth lens group.

The lens system satisfies equations 1-6.

The specific lens parameters for Example 2 are included in Table 2 using the same form as already described for Table 1.

TABLE 2

The optical prescription of Example 2.

Surface	Radius	Thickness	Nd	Abbe#	Lens Element
1	49.32	2.04	1.55	75.50	202
2	13.41	9.45			
3	−36.86	0.72	1.52	64.21	203
4	17.53	19.41			
5	58.43	5.01	1.95	32.32	204
6	−52.14	3.22			
7	19.93	5.01	1.78	25.72	205
8	24.39	6.05			
9	226.55	0.49	1.85	23.79	206
10	13.46	3.67	1.59	68.62	207
11	−34.34	0.09			
STO	Infinity	0.10			
13	29.13	3.34	1.59	68.62	209
14	−14.90	0.56	1.85	23.79	210
15	206.55	11.53			
16	28.73	2.55	1.95	17.94	211
17	Infinity	1.00			
18	Infinity	0.50	1.52	64.21	
19	Infinity	9.24			
20	Infinity	0.70	1.52	64.21	
21	Infinity	0.40			
IMA	Infinity				

Example 3

FIG. **3** shows the layout of Example 3. This design has a field of view of 97.5° with a relative aperture of F/1.8.

There are four groups in lens system **301** of Example 3 comprising, along the optical axis **316**, from the object side to the image side (left to right):

1) Group 1 has negative power consisting of two negative power elements **302**, **303**.
2) Group 2 has positive power comprising 1 to 3 elements, in this example Group 2 is comprised of two lens elements **304**, **305**.
3) In this particular example Group 3 is comprised of a pair of cemented doublets **306**, **307** and **309**, **310** with an aperture stop **308** embedded between the doublets. There is no optional meniscus element in this example. The positive elements **307**, **309** of the cemented doublets are made from a material having low dispersion properties in that the index of refraction and Abbe number of the first positive element **307** are 1.55 and 75.5 respectively and the index of refraction and Abbe number of the positive element **309** of the second doublet are 1.59 and 68.6 respectively. Both positive elements **307**, **309** have a negative value for do/dT.
4) Group 4 has positive power comprising 1 to 3 elements. In this case group 4 is comprised of a two elements **311**, **312**.

The lens elements are all arranged symmetrically about the optical axis **316**. The design further includes an optional optical filter **313** and a cover **314** covering an image sensor located at the focal plane **315**.

The lens system satisfies equations 1-6.

The specific lens parameters for Example 3 are included in Table 3 using the same form as already described for Table 1.

TABLE 3

The optical prescription of Example 3.

Surface	Radius	Thickness	Nd	Abbe#	Lens Element
1	66.41	0.99	1.55	75.50	302
2	11.76	8.32			
3	−19.49	0.73	1.52	64.21	303
4	21.66	10.77			
5	146.95	5.02	1.95	32.32	304
6	−30.98	1.58			
7	22.66	2.36	1.78	25.72	305
8	43.14	8.83			
9	46.23	0.49	1.85	23.79	306
10	14.84	3.83	1.55	75.50	307
11	−28.74	0.10			
STO	Infinity	0.09			
13	22.67	3.31	1.59	68.62	309
14	−14.99	3.72	1.85	23.79	310
15	22.03	8.92			
16	35.64	2.01	1.62	63.41	311
17	137.86	0.07			
18	32.06	3.11	1.95	17.94	312
19	−126.74	1.00			
20	Infinity	0.50	1.52	64.21	
21	Infinity	8.23			
22	Infinity	0.70	1.52	64.21	
23	Infinity	0.40			
IMA	Infinity				

Example 4

FIG. **4** shows the layout of Example 4. This design has a field of view of 97.6° with a relative aperture of F/1.8.

There are four groups in lens system **401** of Example 4 comprising, along the optical axis **415**, from the object side to the image side (left to right):

1) Group 1 has negative power consisting of two negative power elements **402**, **403**.
2) Group 2 has positive power comprising 1 to 3 elements; in this example Group 2 is comprised of two lens elements **404**, **405**.
3) In this particular example Group 3 is comprised of a pair of cemented doublets **406**, **407** and **409**, **410** with an aperture stop **408** embedded between the doublets. There is no optional meniscus element in this example. The positive elements **407**, **409** of the cemented doublets are made from a material having low dispersion properties in that the index of refraction and Abbe number of the first positive element **407** are 1.62 and 63.4, respectively, and, the index of refraction and Abbe number of the positive element **409** of the second doublet are 1.62 and 63.4, respectively. Both positive lens elements **407**, **409** have a negative value for do/dT.
4) Group 4 has positive power comprising 1 to 3 elements. In this case group 4 is comprised of one element **411**.

The lens elements are all arranged symmetrically about the optical axis **415**. The design further includes an optional optical filter **412** and a cover **413** covering an image sensor located at the focal plane **414**.

The lens system satisfies equations 1-6.

The specific lens parameters for Example 4 are included in Table 4 using the same form as already described for Table 1.

TABLE 4

The optical prescription of Example 4.

Surface	Radius	Thickness	Nd	Abbe#	Lens Element
1	45.91	2.00	1.62	63.41	402
2	12.68	10.45			
3	−29.15	0.75	1.52	64.21	403
4	18.04	13.76			
5	54.61	4.90	1.95	32.32	404
6	−44.66	3.00			
7	20.39	4.90	1.78	25.72	405
8	25.96	5.45			
9	Infinity	1.45	1.85	23.79	406
10	14.27	3.38	1.62	63.41	407
11	−31.55	0.10			
STO	Infinity	0.10			
13	30.69	4.90	1.62	63.41	409
14	−12.71	2.00	1.85	23.79	410
15	Infinity	9.65			
16	28.38	2.75	1.95	17.94	411
17	Infinity	2.00			
18	Infinity	0.50	1.52	64.21	
19	Infinity	7.50			
20	Infinity	0.70	1.52	64.21	
21	Infinity	0.40			
IMA	Infinity				

Example 5

FIG. **5** shows the layout of Example 5. This design has a field of view of 145° with a relative aperture of F/2.

There are four groups in lens system **501** of Example 5 comprising, along the optical axis **514**, from the object side to the image side (left to right):

1) Group 1 has negative power and consists of two negative power lens elements **502**, **503**.
2) Group 2 has positive power comprising 1 to 3 elements; in this example Group 2 is comprised of three lens elements **504**, **505**, **506**.
3) In this particular example Group 3 is comprised of a cemented doublet **509**, **510** and positive lens element **508**. An aperture stop **507** is adjacent to lens group 3. There is no optional meniscus element in this example. The positive element **509** of the cemented doublet is made from a material having low dispersion properties in that the index of refraction and Abbe number of the positive element **509** of the doublet are 1.62 and 63.4, respectively. The value of do/dT for the positive element **509** is negative.
4) Group 4 has positive power comprising 1 to 3 elements. In this case group 4 is comprised of one positive lens element **511**.

The lens elements are all arranged symmetrically about the optical axis **514**. The design a cover **512** covering an image sensor located at the focal plane **513**.

The lens system satisfies equations 1-6.

The specific lens parameters for Example 5 are included in Table 5 using the same form as already described for Table 1.

TABLE 5

The optical prescription of Example 5.

Surface	Radius	Thickness	Nd	Abbe#	Lens Element
1	74.06	1.24	1.83	37.23	502
2	11.39	4.85			
3	32.33	1.21	1.74	49.24	503
4	14.59	10.35			
5	−15.04	7.02	2.00	25.44	504
6	−19.87	0.30			
7	37.09	3.96	1.80	46.57	505
8	−73.04	0.10			
9	16.11	4.25	1.74	44.90	506
10	19.39	8.76			
STO	Infinity	0.00			
12	26.33	1.98	1.59	68.62	508
13	−46.69	0.10			
14	13.77	3.03	1.62	63.41	509
15	−9.91	0.40	1.85	23.79	510
16	13.81	5.24			
17	30.24	6.34	1.81	33.29	511
18	−31.51	4.72			
19	Infinity	0.80	1.52	64.21	
20	Infinity	0.40			
IMA	Infinity				

Example 6

FIG. **6** shows the layout of Example 6. This design has a field of view of 145° with a relative aperture of F/2.

There are four groups in lens system **601** of Example 6 comprising, along the optical axis **614**, from the object side to the image side (left to right):

1) Group 1 has negative power and consists of two negative power lens elements **602**, **603**.
2) Group 2 has positive power comprising 1 to 3 elements; in this example Group 2 is comprised of three lens elements **604**, **605**, **606**.
3) In this particular example Group 3 is comprised of a cemented doublet **609**, **610** and positive lens element **608**. An aperture stop **607** is adjacent to lens group 3. There is no optional meniscus element in this example. The positive element **609** of the cemented doublet is made from a material having low dispersion properties in that the index of refraction and Abbe number of the positive element **609** of the doublet are 1.59 and 68.6, respectively. The positive element **609** has a negative value for do/dT.
4) Group 4 has positive power comprising 1 to 3 elements. In this case group 4 is comprised of one element **611**.

The lens elements are all arranged symmetrically about the optical axis **614**. The design a cover **612** covering an image sensor located at the focal plane **613**.

The lens system satisfies equations 1-6.

The specific lens parameters for Example 6 are included in Table 6 using the same form as already described for Table 1.

TABLE 6

The optical prescription of Example 6.

Surface	Radius	Thickness	Nd	Abbe#	Lens Element
1	75.26	1.22	1.79	47.52	602
2	12.07	5.09			
3	32.45	1.30	1.70	55.53	603
4	13.08	10.13			
5	−15.54	6.99	2.00	28.44	604

TABLE 6-continued

The optical prescription of Example 6.					
Surface	Radius	Thickness	Nd	Abbe#	Lens Element
6	−20.82	0.18			
7	36.04	4.30	1.80	46.57	605
8	−59.20	0.30			
9	15.12	2.06	1.72	47.92	606
10	19.82	9.87			
STO	Infinity	0.00			
12	36.57	1.79	1.59	68.62	608
13	−46.01	0.16			
14	14.83	3.02	1.59	68.62	609
15	−9.80	0.40	1.85	23.79	610
16	15.89	4.62			
17	33.95	6.58	2.00	28.44	611
18	−37.12	5.29			
19	Infinity	0.70	1.52	64.21	
20	Infinity	1.00			
IMA	Infinity				

Example 7

FIG. **7** shows the layout of Example 7. This design has a field of view of 51° with a relative aperture of F/1.8.

There are four groups in lens system **701** of Example 7 comprising, along the optical axis **715**, from the object side to the image side (left to right):

1) Group 1 has negative power consisting of one negative power element **702**.
2) Group 2 has positive power comprising 1 to 3 elements; in this example Group 2 is comprised of three lens elements **703**, **704**, **705**.
3) In this particular example Group 3 is comprised of a cemented triplet **707**, **708**, **709**. An aperture stop **706** is adjacent to lens group 3. There is no optional meniscus element in this example. The positive element **709** of the cemented triplet is made from a material having low dispersion properties in that the index of refraction and Abbe number are 1.50 and 81.6, respectively. Positive element **709** has a negative value for do/dT.
4) Group 4 has positive power comprising 1 to 3 elements. In this case group 4 is comprised of three elements **710**, **711**, **712**.

The lens elements are all arranged symmetrically about the optical axis **715**. The design includes a cover **713** covering an image sensor located at the focal plane **714**.

The lens system satisfies equations 1-6.

The specific lens parameters for Example 7 are included in Table 7 using the same form as already described for Table 1.

TABLE 7

The optical prescription of Example 7.					
Surface	Radius	Thickness	Nd	Abbe#	Lens Element
1	−107.48	0.55	1.49	70.44	702
2	14.79	5.46			
3	−15.96	4.38	1.90	37.37	703
4	−19.80	0.06			
5	37.31	2.74	2.00	25.46	704
6	−240.33	5.00			
7	19.99	5.73	1.95	17.98	705
8	11.76	4.52			
STO	Infinity	0.00			
10	26.29	2.53	1.80	46.50	707

TABLE 7-continued

The optical prescription of Example 7.					
Surface	Radius	Thickness	Nd	Abbe#	Lens Element
11	−12.19	5.13	1.85	23.78	708
12	16.35	0.53	1.50	81.56	709
13	7154.83	3.40			
14	77.36	2.98	1.92	20.88	710
15	−21.09	4.81			
16	40.28	0.03	1.55	75.50	711
17	−16.79	5.15	1.80	39.64	712
18	77.15	1.83			
19	Infinity	18.49	1.52	64.21	
20	Infinity	1.37			
IMA	Infinity	0.40			

Example 8

FIG. **8** shows the layout of Example 8. This design has a field of view of 51° with a relative aperture of F/1.8.

There are four groups in lens system **801** of Example 8 comprising, along the optical axis **816**, from the object side to the image side (left to right):

1) Group 1 has negative power consisting of one negative power element **802**.
2) Group 2 has positive power comprising 1 to 3 elements; in this example Group 2 is comprised of two lens elements **803**, **804**.
3) In this particular example Group 3 is comprised of a cemented triplet **806**, **807**, **808** and positive meniscus lens element **809**. An aperture stop **805** is adjacent to lens group 3. The positive element **808** of the cemented triplet is made from a material having low dispersion properties in that the index of refraction and Abbe number are 1.50 and 81.6, respectively. The positive element **808** has a negative value for do/dT.
4) Group 4 has positive power comprising 1 to 3 elements. In this case group 4 is comprised of three elements **810**, **811**, **812**.

The lens elements are all arranged symmetrically about the optical axis **816**. The design includes an optional filter **813** and a cover **814** covering an image sensor located at the focal plane **815**.

The lens system satisfies equations 1-6.

The specific lens parameters for Example 8 are included in Table 8 using the same form as already described for Table 1.

TABLE 8

The optical prescription of Example 8.					
Surface	Radius	Thickness	Nd	Abbe#	Lens Element
1	−64.53	0.75	1.57	56.06	802
2	16.82	8.43			
3	−17.03	7.42	1.88	40.81	803
4	−22.50	0.10			
5	39.73	3.19	2.00	25.44	804
6	−169.81	14.72			
STO	Infinity	0.00			
7	70.55	2.93	1.57	56.06	806
8	−33.60	0.49	1.85	23.79	807
9	18.60	4.45	1.50	81.59	808
10	−30.36	0.15			
11	23.80	5.03	1.74	49.24	809
12	33.02	18.76			
13	41.10	2.73	2.00	25.44	810

TABLE 8-continued

The optical prescription of Example 8.

Surface	Radius	Thickness	Nd	Abbe#	Lens Element
14	−118.59	0.10			
15	23.28	4.62	1.50	81.59	811
16	−62.49	0.72	1.73	54.67	812
17	21.53	2.00			
18	Infinity	0.50	1.52	64.20	
19	Infinity	6.91			
20	Infinity	0.70	1.52	64.20	
21	Infinity	0.40			
IMA	Infinity				

Example 9

FIG. **9** shows the layout of Example 9. This design has a field of view of 51° with a relative aperture of F/1.8.

There are four groups in lens system **901** of Example 9 comprising, along the optical axis **915**, from the object side to the image side (left to right):

1) Group 1 has negative power consisting of one negative power element **902**.
2) Group 2 has positive power comprising 1 to 3 elements; in this example Group 2 is comprised of three lens elements **903**, **904**, **905**.
3) In this particular example Group 3 is comprised of a cemented doublet **907**, **908** and positive lens element **909**. An aperture stop **906** is adjacent to lens group 3. There is no optional meniscus element in this example. The positive element **907** of the doublet is made from a material having low dispersion properties in that the index of refraction and Abbe number are 1.70 and 55.5, respectively. The value for do/dT of element **907** is positive.
4) Group 4 has positive power comprising 1 to 3 elements. In this case group 4 is comprised of three elements **910**, **911**, **912**.

The lens elements are all arranged symmetrically about the optical axis **915**. The design includes an optional cover **913** covering an image sensor located at the focal plane **914**.

The lens system satisfies equations 1-6.

The specific lens parameters for Example 9 are included in Table 9 using the same form as already described for Table 1.

TABLE 9

The optical prescription of Example 9.

Surface	Radius	Thickness	Nd	Abbe#	Lens Element
1	−92.68	0.54	1.49	70.44	902
2	14.47	5.04			
3	−18.82	6.33	1.88	40.81	903
4	−23.76	0.08			
5	31.87	2.82	2.00	25.46	904
6	2421.59	0.79			
7	20.99	5.70	1.95	17.98	905
8	12.97	8.03			
STO	Infinity	0.09			
10	24.26	4.37	1.70	55.46	907
11	−14.00	0.55	1.85	23.78	908
12	31.37	4.78			
13	35.34	4.53	1.50	81.56	909
14	−27.65	0.02			
15	−68.42	2.49	2.10	17.02	910
16	−26.46	0.06			

TABLE 9-continued

The optical prescription of Example 9.

Surface	Radius	Thickness	Nd	Abbe#	Lens Element
17	40.74	5.54	1.55	75.50	911
18	−15.17	0.57	1.81	40.73	912
19	195.65	20.93			
20	Infinity	1.37	1.52	64.21	
21	Infinity	0.46			
IMA	Infinity				

Example 10

FIG. **10** shows the layout of Example 10. This design has a field of view of 51° with a relative aperture of F/1.8.

There are four groups in lens system **1001** of Example 10 comprising, along the optical axis **1015**, from the object side to the image side (left to right):

1) Group 1 has negative power consisting of one negative power element **1002**.
2) Group 2 has positive power comprising 1 to 3 elements; in this example Group 2 is comprised of two lens elements **1003**, **1004**.
3) In this particular example Group 3 is comprised of a cemented triplet **1006**, **1007**, **1008** and positive meniscus lens element **1009**. An aperture stop **1005** is adjacent to lens group 3. The positive lens elements **1006**, **1008** of the triplet are made from material having a high refractive index (1.68, 1.63) and high Abbe number 55.6 and 63.5 respectively. Positive element **1008** has a negative value for do/dT.
4) Group 4 has positive power comprising 1 to 3 elements. In this case group 4 is comprised of two elements **1010**, **1011**.

The lens elements are all arranged symmetrically about the optical axis **1015**. The design includes an optional filter **1012** and a cover **1013** covering an image sensor located at the focal plane **1014**.

The lens system satisfies equations 1-6.

The specific lens parameters for Example 10 are included in Table 10 using the same form as already described for Table 1.

TABLE 10

The optical prescription of Example 10.

Surface	Radius	Thickness	Nd	Abbe#	Lens Element
1	−74.74	1.00	1.64	60.21	1002
2	17.58	7.31			
3	−15.23	7.50	1.76	52.33	1003
4	−20.29	0.39			
5	40.45	4.20	2.00	25.44	1004
6	−170.45	19.13			
STO	Infinity	0.00			
7	52.39	3.50	1.68	55.56	1006
8	−23.20	0.75	1.85	23.79	1007
9	16.38	4.20	1.62	63.41	1008
10	−44.93	0.10			
11	17.56	6.00	1.80	46.57	1009
12	17.05	11.53			
13	35.36	5.25	1.92	20.88	1010
14	−18.20	2.40	1.95	32.32	1011
15	Infinity	2.00			
16	Infinity	0.50	1.52	64.20	
17	Infinity	8.17			
18	Infinity	0.70	1.52	64.20	

TABLE 10-continued

The optical prescription of Example 10.

Surface	Radius	Thickness	Nd	Abbe#	Lens Element
19	Infinity	0.40			
IMA	Infinity				

Example 11

FIG. **11** shows the layout of Example 11. This design has a field of view of 51° with a relative aperture of F/1.8.

There are four groups in lens system **1101** of Example 11 comprising, along the optical axis **1115**, from the object side to the image side (left to right):

1) Group 1 has negative power consisting of one negative power element **1102**.
2) Group 2 has positive power comprising 1 to 3 elements; in this example Group 2 is comprised of two lens elements **1103**,**1104**.
3) In this particular example Group 3 is comprised of a cemented triplet **1106**, **1107**, **1108** and positive meniscus lens element **1109**. An aperture stop **1105** is adjacent to lens group 3. The positive elements **1106**, **1108** of the cemented triplet are also made of materials having a high refractive index and Abbe number. The positive element **1108** has a negative value for do/dT.
4) Group 4 has positive power comprising 1 to 3 elements. In this case group 4 is comprised of two elements **1110**, **1111**.

The lens elements are all arranged symmetrically about the optical axis **1115**. The design includes an optional filter **1112** and a cover **1113** covering an image sensor located at the focal plane **1114**.

The lens system satisfies equations 1-6.

The specific lens parameters for Example 11 are included in Table 11 using the same form as already described for Table 1.

TABLE 11

The optical prescription of Example 11.

Surface	Radius	Thickness	Nd	Abbe#	Lens Element
1	−172.63	1.00	1.62	58.15	1102
2	16.17	9.28			
3	−15.12	7.50	1.62	58.15	1103
4	−20.32	0.10			
5	42.41	4.20	2.00	25.44	1104
6	−124.22	17.92			
STO	Infinity				
7	139.50	3.25	1.68	55.56	1106
8	−21.22	0.75	1.85	23.79	1107
9	17.48	4.20	1.62	63.41	1108
10	−34.73	0.10			
11	21.18	5.50	1.73	54.67	1109
12	26.16	14.39			
13	30.36	3.80	1.92	20.88	1110
14	−46.30	0.74			
15	−40.56	0.90	1.76	52.33	1111
16	56.99	4.00			
17	Infinity	0.50	1.52	64.20	
18	Infinity	5.80			
19	Infinity	0.70	1.52	64.20	
20	Infinity	0.40			
IMA	Infinity				

Example 12

FIG. **12** shows the layout of Example 12. This design has a field of view of 51° with a relative aperture of F/1.8.

There are four groups in lens system **1201** of Example 12 comprising, along the optical axis **1214**, from the object side to the image side (left to right):

1) Group 1 has negative power consisting of one negative power element **1202**.
2) Group 2 has positive power comprising 1 to 3 elements; in this example Group 2 is comprised of two lens elements **1203**, **1204**.
3) In this particular example Group 3 is comprised of a cemented triplet **1206**, **1207**, **1208** and positive meniscus lens element **1209**. An aperture stop **1205** is adjacent to lens group 3. The positive elements **1206**, **1208** of the cemented triplet are also made of materials having a high refractive index and high Abbe number. Positive element **1206** has a negative value for do/dT.
4) Group 4 has positive power comprising 1 to 3 elements. In this case group 4 is comprised of two elements **1210**, **1211**.

The lens elements are all arranged symmetrically about the optical axis **1214**. The design includes an optional filter **1211** and a cover **1212** covering an image sensor located at the focal plane **1213**.

The lens system satisfies equations 1-6.

The specific lens parameters for Example 12 are included in Table 12 using the same form as already described for Table 1.

TABLE 12

The optical prescription of Example 12.

Surface	Radius	Thickness	Nd	Abbe#	Lens Element
1	−246.40	1.00	1.65	33.84	1202
2	15.67	6.94			
3	−14.84	7.55	1.80	46.57	1203
4	−19.86	3.52			
5	33.80	4.24	2.00	25.44	1204
6	−1196.09	17.63			
STO	Infinity				
7	42.80	3.97	1.59	68.62	1206
8	−20.41	0.75	1.85	23.79	1207
9	17.91	4.37	1.52	64.21	1208
10	−29.05	0.07			
11	18.31	6.11	1.92	20.88	1209
12	19.04	14.52			
13	22.95	2.59	1.95	17.94	1210
14	48.28	2.00			
15	Infinity	0.50	1.52	64.20	
16	Infinity	7.87			
17	Infinity	0.70	1.52	64.20	
18	Infinity	0.40			
IMA	Infinity				

Examples Summary

The effective focal length F of the entire lens assembly, F1 of group 1, F2 of group 2, F3 of group 3 and F4 of group 4 are shown in Tables 13A and 13B. The examples in Table 13A all have an effective focal length of 10.2 or less and a field of view between 97° and 145°. The examples summarized in Table 13B all have an effective focal length of about 18.5 and a field of view of about 50°. All of the examples summarized in both tables 13A and 13B are described per the four lens groups and the details of each as discussed repeatedly above as well as the six parametric equations (1)-(6), repeated here for convenience.

TABLE 13A

Summary of Lens parameters for Examples 1-6						
Example	1	2	3	4	5	6
F of entire lens assembly	10.2	9.8	10.0	9.8	6.83	6.83
F1 of group 1	−11.3	−11.8	−9.5	−10.2	−10.1	−10.4
F2 of group 2	24.2	21.7	18.6	19.7	18.8	18.1
F3 of group 3	52.8	333.3	−232.1	128.2	108.1	1411
F4 of group 4	30.1	30.4	20.6	30.0	20.0	18.4
F1/F	−1.1	−1.2	−0.9	−1.0	−1.48	−1.52
F2/F	2.4	2.2	1.9	2.0	2.75	2.65
|F3/F|	5.2	33.8	23.1	13.1	15.83	206.6
F4/F	3.0	3.1	2.0	3.1	2.9	2.7
F4/F1	−2.7	−2.6	−2.2	−2.9	−2.0	−1.8
F4/F2	1.2	1.4	1.1	1.5	1.1	1.8

TABLE 13B

Summary of Lens parameters for Examples 7-12						
Example	7	8	9	10	11	12
F	18.5	18.6	18.5	18.6	18.6	18.6
F1	−26.6	−23.4	−25.6	−22.2	−23.7	−22.7
F2	61.7	30.7	52.5	30.9	30.7	30.1
F3	124.9	105.0	41.7	79.1	79.8	82.2
F4	20.3	42.2	45.8	40.8	48.6	44.1
F1/F	−1.4	−1.3	−1.4	−1.2	−1.3	−1.2
F2/F	3.3	1.6	2.8	1.7	1.7	1.6
|F3/F|	6.7	5.6	2.3	4.3	4.3	4.4
F4/F	1.1	2.3	2.5	2.2	2.6	2.4
F4/F1	−0.8	−1.8	−1.8	−1.8	−2.1	−1.9
F4/F2	0.3	1.4	0.9	1.3	1.6	1.5

The following conditions are satisfied:

$$-2=<F1/F=<-0.8 \qquad (1)$$

$$1.5=<F2/F=<3.5 \qquad (2)$$

$$2.=<|F3/F| \qquad (3)$$

$$1.=<F4/F=<3.5 \qquad (4)$$

$$-3=<F4/F1=<-0.6 \qquad (5)$$

$$0.2=<F4/F2=<2. \qquad (6)$$

In preferred embodiments the following equation is satisfied by Group 1:

$$-1.6=<F1/F=<-0.8 \qquad (7)$$

SUMMARY

High performance lens system designs are described. The lens system has four lens groups, is made entirely of spherical lens elements, and, includes selected lens elements made of materials with high refractive index and Abbe numbers and coefficient of thermal expansion that provide stable high performance across wide and rapid temperature changes. Group descriptions and parametric equations enable creation of designs having fields of view ranging from 50 to 150 degrees.

We claim:

1. An optical lens for imaging, said lens having an effective focal length, a field of view, and optical axis and an image plane, and, said optical lens comprising:

a. four lens groups located along the optical axis in order from object to image group 1, group 2, group 3, and, group 4, each group having an effective focal length, and,

b. group 1 has negative power consisting of one or two lens elements, all lens elements in group 1 have negative power, and, −1.6=<F1/F=<−0.8, where F is the effective focal length of the optical lens, F1 is the effective focal length of group 1, and,

c. group 2 has positive power comprising 1 to 3 elements, and,

d. group 3 comprises a meniscus lens, and, a cemented doublet or a cemented triplet, the cemented doublet or cemented triplet having at least one positive element, and, where at least one of the at least one positive element is made of material having an Abbe number greater than 63, and,

e. group 4 has positive power comprising 1 to 3 elements.

2. The optical lens of claim **1** that satisfies the parametric equations:

$$1.5=<F2/F=<3.5 \qquad a.$$

$$2.=<|F3/F| \qquad b.$$

$$1.=<F4/F=<3.5 \qquad c.$$

$$-3=<F4/F1=<-0.6 \qquad d.$$

$$0.3=<F4/F2=<2.5 \qquad e.$$

where F is the effective focal length of the optical lens, F1 is the effective focal length of group 1, F2 is the effective focal length of group 2, F3 is the effective focal length of group 3, and, F4 is the effective focal length of group 4.

3. An optical lens for imaging, said lens having an effective focal length, a field of view, and optical axis and an image plane, and, said optical lens comprising:

a. four lens groups located along the optical axis in order from object to image group 1, group 2, group 3, and, group 4, each group having an effective focal length, and,

b. group 1 has negative power consisting of one or two lens elements, and, lens elements in group 1 have negative power, and,

c. group 2 has positive power comprising 1 to 3 elements, and,

d. group 3 comprises a meniscus lens, and, a cemented doublet or a cemented triplet, the cemented doublet or cemented triplet having at least one positive element, and, where at least one of the at least one positive element is made of material having a negative dn/dT, where n is the index of refraction of the material at d-line, and T is a temperature of an environment containing the optical lens, and,

e. group 4 has positive power comprising 1 to 3 elements.

4. The optical lens of claim **3** where group 3 comprises a cemented doublet or a cemented triplet, the cemented doublet or cemented triplet having at least one positive element, and, where at least one of the at least one positive element is made of material having an Abbe number greater than 63.

5. The optical lens of claim **3** that satisfies the parametric equations:

$$-1.6=<F1/F=<-0.8 \qquad a.$$

where F is the effective focal length of the optical lens, F1 is the effective focal length of group 1.

6. The optical lens of claim 3 that satisfies the parametric equations:

$$-2=<F1/F=<-0.8 \quad a.$$

$$1.5=<F2/F=<3.5 \quad b.$$

$$2.=<1F3/F1 \quad c.$$

$$1.=<F4/F=<3.5 \quad d.$$

$$-3=<F4/F1=<-0.6 \quad e.$$

$$0.3=<F4/F2=<2.5 \quad f.$$

where F is the effective focal length of the optical lens, F1 is the effective focal length of group 1, F2 is the effective focal length of group 2, F3 is the effective focal length of group 3, and, F4 is the effective focal length of group 4.

7. An optical lens for imaging, said optical lens having an effective focal length, and, an optical axis, and, said optical lens consisting of:

a. four lens groups located along the optical axis in order from object to image group 1, group 2, group 3, and, group 4, each lens group having an effective focal length, and,

b. group 1 has negative power consisting of one or two lens elements, and, all lens elements in group 1 have negative power, and,

c. group 2 has positive power consisting of 1 to 3 elements, and,

d. group 3 consists of a cemented doublet or a cemented triplet, the cemented doublet or cemented triplet having at least one positive element, and, having an Abbe number greater than 63 and a negative do/dT, where n is the index of refraction of the material at d-line, and T is a temperature of an environment containing the optical lens, and,

e. group 4 has positive power consisting of 1 to 3 elements, and,

f. the optical lens satisfies the parametric equations:

$$-2=<F1/F=<-0.8 \quad i.$$

$$1.5=<F2/F=<3.5 \quad ii.$$

$$2.=<|F3/F| \quad iii.$$

$$1.=<F4/F=<3.5 \quad iv.$$

$$-3=<F4/F1=<-0.6 \quad v.$$

$$0.3=<F4/F2=<2.5 \quad vi.$$

where F is the effective focal length of the optical lens, F1 is the effective focal length of group 1, F2 is the effective focal length of group 2, F3 is the effective focal length of group 3, and, F4 is the effective focal length of group 4.

8. The optical lens of claim 7 that satisfies the parametric equations:

$$-1.6=<F1/F=<-0.8 \quad a.$$

where F is the effective focal length of the optical lens, F1 is the effective focal length of group 1.

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